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Modal variability in the Southeast Pacific Basin: Energetics of the 2009 event

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ABSTRACT

We study the barotropic variability in the Southeast Pacific Basin, in particular focusing on the extreme event during the fourth quarter of 2009. A 3-year integration of a barotropic shallow-water model forced with wind stress anomalies generates localized variability that is similar in spatial extent and amplitude as the observed anomalous event. An eigenmode analysis of the same model shows the presence of several free modes in the Southeast Pacific, but projection of the modal patterns on the model output shows that their amplitudes are low. Instead, the mode is interpreted as an *almost*-free mode. The modal excitation accounts for a considerable fraction (23% on average) of the kinetic energy input by the wind stress in the Southeast Pacific Basin, increasing to 38% for the anomalous event in 2009. Surprisingly, a similar but weaker event during the third quarter of 2008 appears to have been more significant from an energetics point of view, with almost 50% of the energy being input into the mode. Key areas of energetic dissipation appear to be the Eltanin Fracture Zone, the crest of the East Pacific Rise, and the Chile Rise/East Pacific Rise intersection.

1. Introduction

Several ocean basins exhibit significant barotropic variability on intraseasonal scales (Chao and Fu, 1995; Fu and Smith, 1996; Fu, 2003; Vivier et al., 2005). Specific areas in the Southern Ocean with significantly enhanced levels of sea surface height (SSH) variability are the Australian–Antarctic Basin (Webb and De Cuevas, 2002a; Weijer et al., 2009; Weijer, 2010), the Argentine Basin (Fu et al., 2001; Hughes et al., 2007; Weijer et al., 2007a), and the Bellingshausen Basin (Webb and De Cuevas, 2002b, 2003). These basins are characterized by contours of potential vorticity f/H (where f is the Coriolis parameter and H is the water depth) that are closed or almost closed around isolated bathymetric features, like abyssal plains, ridge segments or large seamounts.

In principle, circulation along closed contours of f/H, is free in the sense of being unconstrained by vorticity dynamics, and once excited, is damped mainly by frictional effects (Koblinsky, 1990). In practice, however, also flow along *almost* closed contours of f/H can be excited, termed almost-free modes by Hughes et al. (1999), who used this concept to describe a band of enhanced SSH variability around Antarctica. Rather than being damped by friction, the circulation loses most of its energy to waves at a few choke points, where the flow has to cross contours of f/H to complete the circuit. This leads to a decay time on the order of days (Webb and De Cuevas, 2003), compared to several weeks for purely free modes (Weijer et al., 2009). In two recent studies (Weijer et al., 2009; Weijer, 2010) it was shown that the strong intraseasonal variability in the Australian–Antarctic Basin can be ascribed mostly to such an almost-free mode, with a smaller contribution from purely modal circulation.

The potential significance of these modes is that it provides a direct route via which wind energy can be dissipated through interaction with bathymetry. In particular, Weijer (2010) showed that the almost-free mode in the AAB loses a significant fraction of its energy at the apex of the Wilkes Abyssal Plain, both to bottom friction, as well as to wave generation.

Recently, Boening et al. (2011) described an exceptional episode in the Southeast Pacific Basin: during the fourth quarter of 2009 a persistent anomalous anti-cyclonic circulation was recorded in SSH and bottom pressure (BP) records that was unprecedented for the entire lengths of the observational records. A link was made between the excitation of this mode and an anomalously strong and persistent high pressure anomaly, which may have been related to an anomalous Central Pacific El-Niño event (Lee et al., 2010). This link is significant, because of the apparent recent change in the recurrence frequency of Central Pacific El-Niños, compared to the traditional eastern Pacific variety (Ashok et al., 2007).

In this paper we study the dynamics and energetics of the 2009 event in the Southeast Pacific Basin (Fig. 1). In particular we address (i) to what extent the anomalous circulation can be ascribed to free and almost-free topographically trapped modes, and (ii) what this implies for the energetics of the

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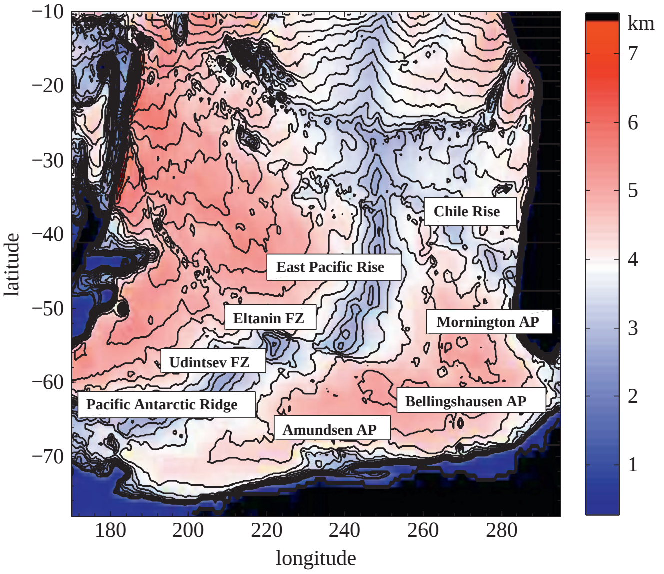

Fig. 1. Bathymetry of the South Pacific (shading, in km depth) with some relevant geographic features (FZ=Fracture Zone; AP=Abyssal Plain). Contours are isolines of ${}^{10}\log(|f|/H)$, plotted for the interval [−9.0,−7.0] with step 0.05.

barotropic circulation in the Southeast Pacific Ocean. To that end, we perform a normal mode analysis on a shallow-water model of the South Pacific, and perform time-integrations with the same model, to study modal/non-modal energetic interactions.

2. Method

The code used here is based on the shallow-water model introduced by Dijkstra and Molemaker (1999), Dijkstra et al. (1999), and Dijkstra and De Ruijter (2001), modified to account for bathymetry, and used to study topographically trapped variability by Weijer et al. (2007a,b, 2009) and Weijer (2008, 2010). The shallow-water model is configured for the region [170°E, 295°E], and [78°S, 10°S], with a spatial resolution of 0.5°. Bathymetry is based on the ETOPO-2 dataset, interpolated onto the model grid, and smoothed once with a 1-4-1 smoother. Maximum depth is 7600 m. As in Weijer et al. (2009), horizontal viscosity A_h is set at $3\times10^3\ \mathrm{m^2\ s^{-1}}$, with a linear bottom friction coefficient $r=2\times10^{-7}\ \mathrm{s^{-1}}$ ($1/58\ \mathrm{day}^{-1}$).

Coefficients of horizontal eddy viscosity are poorly constrained in the ocean, and range from $5\times10^3\ \mathrm{m^2 s^{-1}}$ (Munk, 1950) to $50\ \mathrm{m^2\ s^{-1}}$ (Polzin, 2010). In most numerical studies, the value is chosen so that the Munk scale is resolved. With the value used here, this scale is resolved by at least two grid points only south of 56°S, and is hence marginally sufficient. Estimates of bottom friction range from $1\times10^{-7}\ \mathrm{s^{-1}}$ (Nowlin, 1967) to $5\times10^{-6}\ \mathrm{s^{-1}}$ (Hirose et al., 2001), and the value used here is at the lower end of this range. To test the robustness of the results with respect to this parameter choice, we repeated the time integration with the values $A_h=3\times10^2\ \mathrm{m^2\ s^{-1}}$ and $r=1\times10^{-7}\ \mathrm{s^{-1}}$.

Wind forcing is derived from the Cross-Calibrated Multi-Platform (CCMP) Ocean Surface Wind Velocity, which is available from 1987 onward (Atlas et al., 1996, 2011). The data are provided 6-hourly on a 0.25° grid. We use the 10 m wind fields from January 1, 2008, through December 31, 2010. First, the wind velocities are converted to wind stress using the Large and Pond (1982) relation. Then the 6-hourly vector fields are averaged to daily values, the annual and semi-annual cycles are removed, and the data are detrended. Despite removal of the *mean* seasonal cycle, the variance of the wind stress still displays strong seasonality.

The shallow-water model is used to calculate normal modes of the Southeast Pacific barotropic circulation. As in our previous studies, the Jacobi–Davidson QZ (JDQZ) method is used to solve the generalized eigenvalue problem (Sleijpen and van der Vorst, 1996; van Dorsselaer, 1997; Dijkstra et al., 2001), along with the MRILU method for preconditioning the sparse numerical systems (Botta and Wubs, 1999; Dijkstra et al., 2001). In addition, the same model is integrated forward in time for a full 3 years (1096 days), using a Crank–Nicolson time stepping scheme with a 15 min time step. Daily averages of sea surface height (SSH, or η), and the zonal (u) and meridional (v) velocity components are saved.

3. Results

3.1. Time integration

Fig. 2 shows the mean SSH from the shallow-water model for the last 3 months of 2009, which corresponds to the time period for which Boening et al. (2011) found the largest anomalies in SSH and bottom pressure. The model clearly reproduces the large ($O(0.1\ \mathrm{m})$) anomalies in the Southeast Pacific Basin (roughly between 230°E and 280°E (80°W–130°W), and 65°S and 35°S) that is evident from the bottom pressure and SSH observations.

SSH anomaly time series averaged over the 90°W–140°W, 55°S–35°S region are shown in Fig. 3a for comparison with Fig. 1e of Boening et al. (2011). Maximum monthly values reach

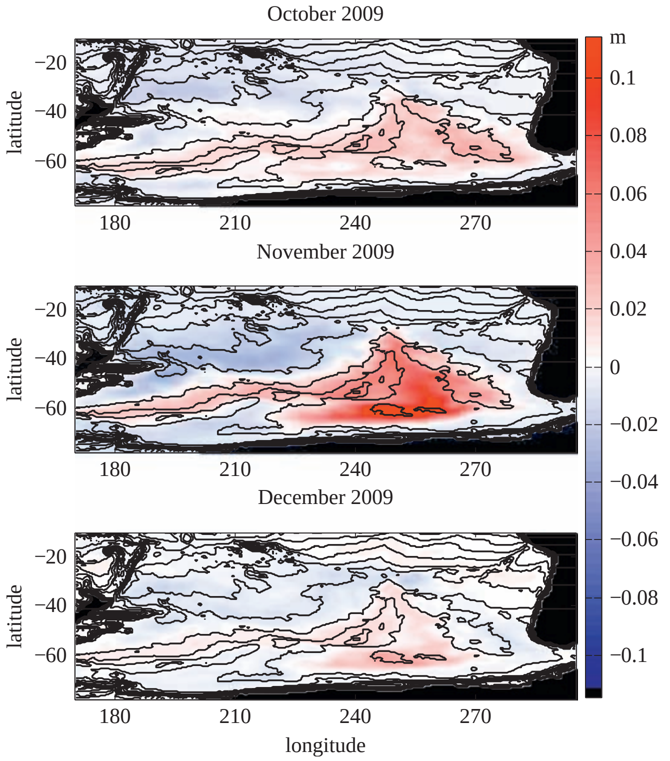

Fig. 2. Average SSH (m) for the months of October, November and December 2009.